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# Nature and decay of a $J^\pi=36^+$ resonance in the $^{24}\text{Mg} + ^{24}\text{Mg}$ reaction

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**Abstract.** It has been proposed to associate the narrow ( $\Gamma=170$  keV) and high spin ( $J^\pi=36^+$ ) resonance in the  $^{24}\text{Mg} + ^{24}\text{Mg}$  reaction at  $E_{\text{c.m.}}=45.7$  MeV with a hyperdeformed molecular state in  $^{48}\text{Cr}$ . Such a description has important consequences for the resonance decay into the favoured inelastic channels. Through fragment- $\gamma$  coincidence measurements performed ON and OFF resonance using the PRISMA-CLARA array, we have established that the  $^{24}\text{Mg}$  states selectively populated are the  $2^+$  and  $4^+$  members of the ground state band.

**Keywords:** NUCLEAR REACTIONS  $^{24}\text{Mg}$  ( $^{24}\text{Mg}$ ,  $^{24}\text{Mg}$ ),  $E_{\text{c.m.}}=45.7$  MeV; measured (fragment) ( $\gamma$ ); deduced ON resonance selective feeding of the  $^{24}\text{Mg}$   $2^+$  and  $4^+$  states.

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## INTRODUCTION

Resonant phenomena are well established in light heavy ion collisions. They have been mainly observed in the elastic and inelastic channels of reactions with composite systems between  $^{24}\text{Mg}$  ( $^{12}\text{C}+^{12}\text{C}$ ) and  $^{56}\text{Ni}$  ( $^{28}\text{Si}+^{28}\text{Si}$ ). The connection between resonances and molecular states in the composite system is still under question.

To better determine this connection, the best cases to study are those for which the resonance width is narrow ( $\sim 100$ - $200$  keV) and the eventually formed dinucleus having a long lifetime, can thus be assimilated to a nuclear molecule. These conditions are fulfilled for the reaction  $^{24}\text{Mg}+^{24}\text{Mg}$ , where narrow resonance phenomena occur at high spin and high excitation energy of the dinucleus  $^{48}\text{Cr}$ .

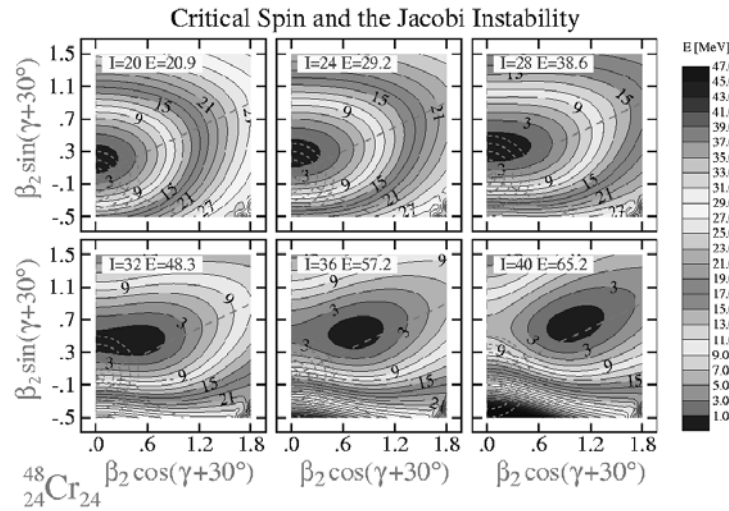
Our present study is focused on the decay of a narrow  $^{24}\text{Mg}+^{24}\text{Mg}$  resonance at  $E_{\text{c.m.}}=45.7$  MeV, whose properties (spin and width) are well known:  $J^\pi=36^+$  and  $\Gamma=$

170 keV [1,2]. The goal of our experiment was to measure for this reaction the ON and OFF resonance decay yields into the various inelastic channels.

Before presenting our experimental results, we would like in this introduction to bring up some general considerations about the possible analogy between this  $^{24}\text{Mg}+^{24}\text{Mg}$  narrow and high spin resonance and a very deformed  $^{48}\text{Cr}$  dinucleus. A resonance width of 170 keV implies a lifetime of  $4.10^{-21}$  s, this is 10 times longer than a typical nuclear lifetime and corresponds to a rotation of  $\sim 2$  turns of the composite system, which gives credit to the formation of a  $^{48}\text{Cr}$  dinucleus in the resonance process.

The resonance under study has a very high spin ( $J^\pi = 36^+$ ) and it is known that for the  $^{48}\text{Cr}$  nucleus the fission barrier vanishes at spin  $\sim 40$ . For this relatively light nucleus, the rotational frequency close to the fission limit is very large and a Jacobi shape transition can be expected [3]. Calculations of the  $^{48}\text{Cr}$  shape evolution were performed using a new version of the liquid drop model that accounts explicitly for the nuclear surface curvature effects. Details concerning the Lublin – Strasbourg - Drop (LSD) approach can be found in Refs. [4,5]. The results for  $^{48}\text{Cr}$  can be seen on Fig. 1. For  $I=20$  to  $I=24$ , the shape of the nucleus is oblate; from  $I=28$  to 32, the Jacobi transition begins and the nucleus becomes triaxial; for  $I=36$  (our resonance spin), the shape is strongly prolate and the excitation energy predicted by this macroscopic model is close to the resonance excitation energy of 60 MeV. Finally, for  $I=40$ , the fission barrier gets small and the nucleus is about to fission.

The suggestion we make here is that there is a possibility of a strong overlap between the entrance channel  $^{24}\text{Mg}+^{24}\text{Mg}$  resonance and the very deformed prolate  $^{48}\text{Cr}$  nucleus at spin  $J^\pi = 36^+$  and excitation energy of 60 MeV.



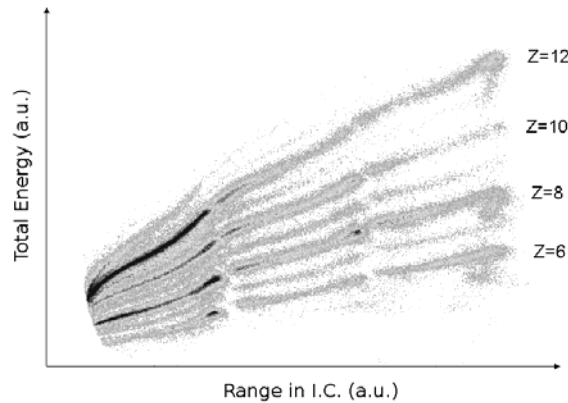
**FIGURE 1.** Total energy calculations in terms of the standard  $(\beta - \gamma)$  deformations according to the LSD approach for the nucleus  $^{48}\text{Cr}$  at spins  $I$  between 20 and 40.

## The Experiment and its Analysis

From previous experiments [1], it is known that in the  $^{24}\text{Mg}+^{24}\text{Mg}$  reaction resonant effects are seen in the elastic and inelastic  $(0^+, 0^+)$ ,  $(2^+, 0^+)$  and  $(2^+, 2^+)$  channels

involving the first two members of the  $^{24}\text{Mg}$  ground state band. In these experiments, where only fragments were detected and consequently limited energy resolution achieved, the contribution to the resonant process of higher lying states could not be determined. It was the goal of the present experiment to get information concerning the feeding of the  $4^+$  and  $6^+$  members of the ground state (g.s.) band and also of members of the  $K^\pi=2^+$  band. In order to have a better resolution, we not only detected the fragments but also the  $\gamma$  rays in coincidence. The  $^{24}\text{Mg}$  fragments produced in the reaction were detected and identified in the PRISMA spectrometer [6]. The detection angular range was  $43^\circ \pm 6^\circ$ , i.e. inside a range where resonances in the studied reaction have been observed previously [1]. The  $\gamma$  rays emitted by the fragments have been detected in coincidence using the CLARA array composed of 24 clover detectors [7].

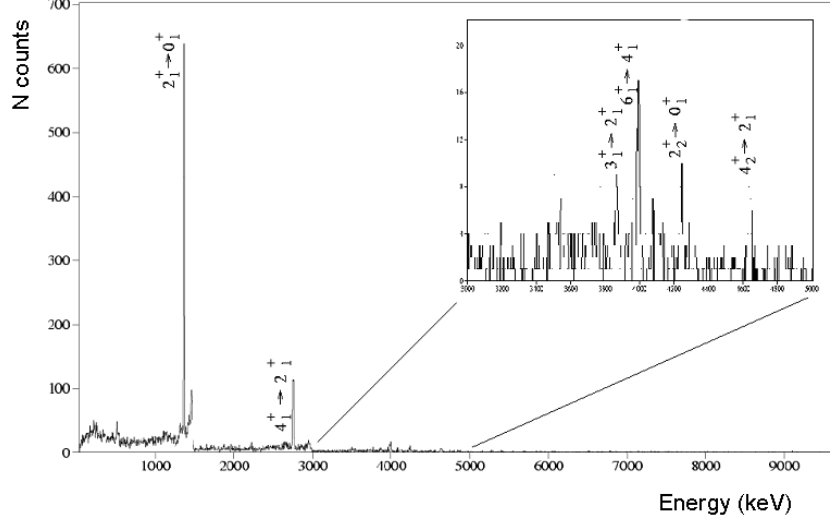
The decay into the inelastic channels has been measured ON and OFF resonance. The  $^{24}\text{Mg} + ^{24}\text{Mg}$  reaction has been studied at the Legnaro XTU Tandem using a  $^{24}\text{Mg}$  beam of 91.72 MeV for the ON resonance measurement and of 92.62 MeV for the OFF resonance measurement. The target consisted of a thin film of  $^{24}\text{Mg}$  ( $40 \mu\text{g}/\text{cm}^2$ ) deposited on a  $^{12}\text{C}$  ( $15 \mu\text{g}/\text{cm}^2$ ) backing. Special care has been taken in the adjustment of the  $90^\circ$  beam analysing magnet in order to avoid hysteresis effects.



**FIGURE 2.** Z distributions obtained in the PRISMA ionization chambers of the  $^{24}\text{Mg}$  induced reactions on a  $^{24}\text{Mg}$  target with  $^{12}\text{C}$  backing.

In PRISMA [6], the fragments are identified in Z and A and their velocity vectors are determined. The fragment Z selection is illustrated on Fig. 2, which shows total energy versus range measured using the PRISMA focal plane ionization chambers. In this spectrum, the fragments come from the reactions  $^{24}\text{Mg}$  on  $^{24}\text{Mg}$  and  $^{12}\text{C}$  (backing). It is seen that the  $\alpha$ -like  $^{12}\text{C}$ ,  $^{16}\text{O}$ ,  $^{20}\text{Ne}$ ,  $^{24}\text{Mg}$  and  $^{28}\text{Si}$  nuclei are preferentially populated compared to the odd Z nuclei. This is due to Q-value effects. For each Z, the fragment data have been analysed to check whether the parameters of the events collected (angle, velocity) fulfilled the kinematics of real binary events in an experiment where only one binary fragment is detected.

In our experiment, the  $\gamma$  rays emitted by the fragments have been detected in coincidence using CLARA. The  $\gamma$  spectrum in coincidence with the selected  $^{24}\text{Mg}$  fragments is shown on Fig. 3. An accurate determination of the fragment velocity



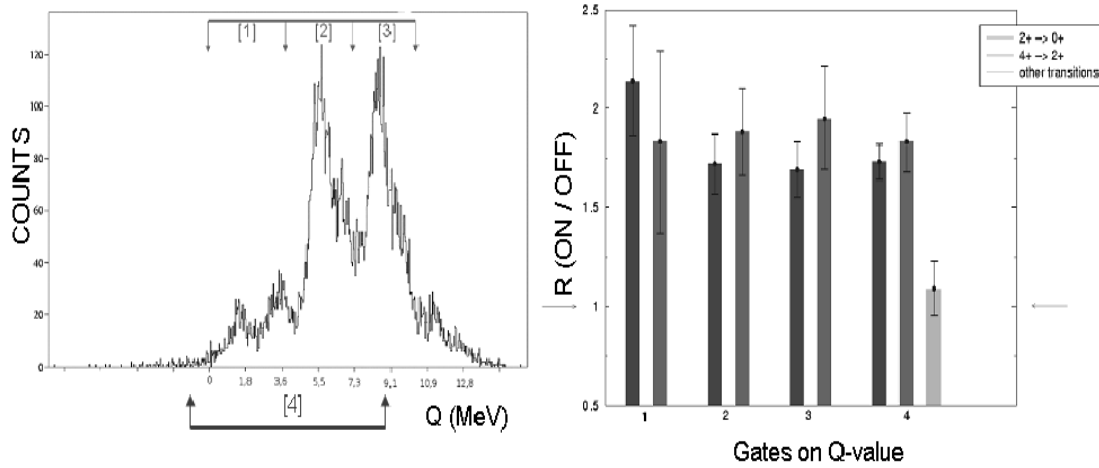
**FIGURE 3.** Gamma spectrum in coincidence with  $^{24}\text{Mg}$  fragments.

vector in PRISMA allows a rather precise Doppler correction of the corresponding  $\gamma$ -ray energy spectrum. For a fragment velocity  $\beta$  of 6%, a resolution of 0.6% has been obtained for the  $2^+_{11} \rightarrow 0^+_{11}$   $^{24}\text{Mg}$  transition with  $E_\gamma = 1369$  keV. In the  $\gamma$  spectrum on Fig. 3, the two predominant lines correspond to the  $^{24}\text{Mg}$  transitions  $2^+_{11} \rightarrow 0^+_{11}$  with  $E_\gamma = 1369$  keV and  $4^+_{11} \rightarrow 2^+_{11}$  with  $E_\gamma = 2753$  keV, where the  $0^+_{11}$ ,  $2^+_{11}$  and  $4^+_{11}$  are the first members of the  $^{24}\text{Mg}$   $K^\pi = 0^+$  g.s. band. At higher energies, weaker lines are observed (see inset of Fig. 3), they correspond to transitions with  $E_\gamma = 3991$  keV ( $6^+_{11} \rightarrow 4^+_{11}$ ), 3867 keV ( $3^+_{11} \rightarrow 2^+_{11}$ ), 4238 keV ( $2^+_{22} \rightarrow 0^+_{11}$ ) and 4642 keV ( $4^+_{22} \rightarrow 2^+_{11}$ ). The  $6^+_{11}$  level belongs to the g.s. band and the  $2^+_{22}$ ,  $3^+_{11}$  and  $4^+_{22}$  to the  $^{24}\text{Mg}$   $K^\pi = 2^+$  band. Looking at the  $\gamma$  spectrum on Fig. 3 and at the two strongest lines, broad components lying beneath the narrow lines can be observed. They correspond to incorrectly Doppler corrected  $\gamma$  rays emitted by the non-detected  $^{24}\text{Mg}$  of the  $^{24}\text{Mg} + ^{24}\text{Mg}$  binary exit channel. From this  $\gamma$  spectrum, it is already obvious that the inelastic channel is dominated by the selective feeding of the  $2^+_{11}$  and  $4^+_{11}$  states in  $^{24}\text{Mg}$ . This point will be explicitly discussed in the next section of the present article.

## Results and Discussion

In order to determine which states in the inelastic channels carry away the resonant flux, the yields of the corresponding  $\gamma$ -ray transitions have been measured ON and OFF resonance energies. On Fig. 4 are represented the obtained Q spectrum (left) of the  $^{24}\text{Mg} + ^{24}\text{Mg}$  inelastic channel and the ratio R of these yields (right) for different transitions and different Q-value gates. Of course, if R equals 1 there is no resonance effect. The first gate on Q corresponds to an inelastic excitation energy between 0.3 and 4.1 MeV and thus to the  $^{24}\text{Mg}$  channels ( $2^+_{11}, 0^+_{11}$ ), ( $2^+_{11}, 2^+_{11}$ ) and ( $4^+_{11}, 0^+_{11}$ ). For both

transitions  $2^+_{11} \rightarrow 0^+_{11}$  and  $4^+_{11} \rightarrow 2^+_{11}$ ,  $R$  equals approximately 2 and thus both  $2^+_{11}$  and  $4^+_{11}$  states are resonant states, the strongest contribution in this gate comes from the  $(2^+_{11}, 2^+_{11})$  channel. The second gate on  $Q$ -value corresponds to an excitation energy between 4.1 and 6.9 MeV. For this gate, a resonant effect is seen again in the yields of the  $2^+_{11} \rightarrow 0^+_{11}$  and  $4^+_{11} \rightarrow 2^+_{11}$  transitions. In this gate, the main contribution comes from the  $(4^+_{11}, 2^+_{11})$  channel. The ratio  $R$  for  $2^+_{11} \rightarrow 0^+_{11}$  is smaller than for  $4^+_{11} \rightarrow 2^+_{11}$ , this can probably be explained by a weak feeding of  $2^+_{11}$  by states of the  $K^\pi=2^+$  band, which will be shown later to be non-resonant. The third gate corresponds to an excitation energy between 6.9 and 10 MeV. As before, a resonant effect is seen in the yields of  $2^+_{11} \rightarrow 0^+_{11}$  and  $4^+_{11} \rightarrow 2^+_{11}$ , in this gate the main contribution comes from the  $(4^+_{11}, 4^+_{11})$  channel. Finally the fourth gate corresponds to the total excitation energy from 0.3 to 10 MeV. The  $2^+_{11} \rightarrow 0^+_{11}$  and  $4^+_{11} \rightarrow 2^+_{11}$  show strong resonant effects, the yields of the other transitions (see inset on Fig. 3) are weak and non-resonant ( $R \sim 1$ ).

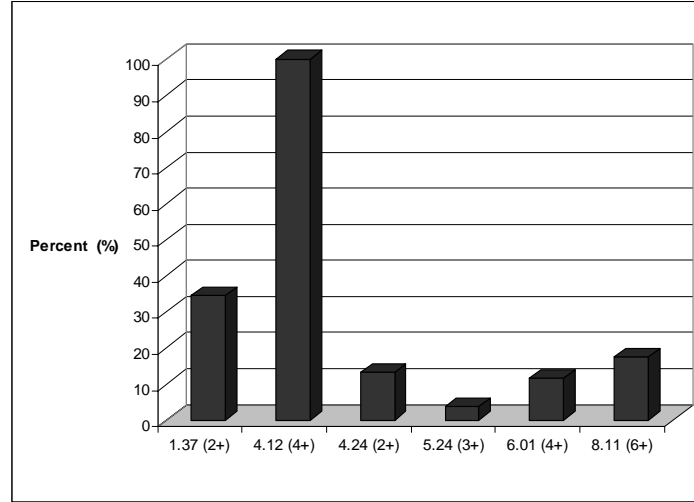


**FIGURE 4.** Left:  $Q$  spectrum of the  $^{24}\text{Mg} + ^{24}\text{Mg}$  inelastic channels with indication of the different gates considered. Right: ON and OFF yield ratios  $R$  for different  $^{24}\text{Mg}$  transitions and  $Q$ -value gates.

For the ON resonance measurement, the direct feeding yields in the inelastic channel of the different  $^{24}\text{Mg}$  states have been extracted and are represented on Fig. 5. It is obvious that for the  $^{24}\text{Mg}$  excitation energy region investigated in our experiment, the  $2^+_{11}$  and moreover the  $4^+_{11}$  play an essential role in the decay of the  $^{24}\text{Mg} + ^{24}\text{Mg}$  resonance.

To put it in a nutshell, the  $^{24}\text{Mg} + ^{24}\text{Mg}$  resonance decay flux is essentially observed in the  $^{24}\text{Mg}$   $4^+_{11}$  and  $2^+_{11}$  states (present measurements) and also in the elastic channel from previous measurements [1,2], i.e. in the first three members of the  $^{24}\text{Mg}$   $K^\pi=0^+$  ground state band. This is in agreement with the molecular model proposed by Uegaki and Abe [8] to describe the  $^{24}\text{Mg} + ^{24}\text{Mg}$  high spin resonances, in which the main collective motions of the system are taken into account and the nucleus – nucleus interaction is described by a folding potential. The equilibrium shape obtained is very deformed, it is a prolate pole-to-pole configuration which is very similar to the  $^{48}\text{Cr}$  shape obtained after the Jacobi transition and before fission (see Fig. 1). The identification of the  $J^\pi=36^+$  resonance at  $E_{\text{c.m.}}=45.7$  MeV with a  $^{48}\text{Cr}$  hyperdeformed molecular state is in agreement with the molecular model predictions what excitation

energy, spin and decay are concerned. In this picture, the ground state  $^{24}\text{Mg}$  rotational band and especially the  $0^+$ ,  $2^+$  and  $4^+$  states play the dominant role in the description and in the decay of the resonance as demonstrated in our experiment and in previous work [1,2].



**FIGURE 5.** ON resonance direct feeding of the  $^{24}\text{Mg}$  states in the  $^{24}\text{Mg} + ^{24}\text{Mg}$  inelastic channel.

## CONCLUSION

We have demonstrated in our experiment that the resonant flux of the  $^{24}\text{Mg} + ^{24}\text{Mg}$   $J^\pi=36^+$  resonance at  $E_{c.m.}=45.7$  MeV is essentially carried away in the inelastic channels by the  $^{24}\text{Mg}$   $2^+_1$  and  $4^+_1$  states. It is known that for the  $^{24}\text{Mg} + ^{24}\text{Mg}$  reaction the elastic and inelastic channels are ten times stronger than the  $\alpha$  transfer channels and that all the direct reaction channels absorb only 30% of the resonance flux [2]. Compound nucleus statistical model calculations done with the code Cacarizo indicate that this flux corresponding to the highest partial wave in the entrance channel can be preferentially evacuated through the  $2\alpha$  fusion channel leading to  $^{40}\text{Ca}$ . We propose therefore in an upcoming experiment to search for the missing resonance flux in the  $^{24}\text{Mg}(^{24}\text{Mg}, 2\alpha \text{ or } ^8\text{Be})^{40}\text{Ca}$  fusion evaporation channels feeding the deformed and superdeformed bands in  $^{40}\text{Ca}$ . In the case of ON resonance selective feeding, this would establish a link between the  $^{48}\text{Cr}$  molecular state and the  $^{40}\text{Ca}$  superdeformed states, which will be a clear proof that a very deformed  $^{48}\text{Cr}$  dinucleus has been produced through the entrance channel  $^{24}\text{Mg}+^{24}\text{Mg}$  resonance process.

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